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RESEARCH MEMORANDUM

THE USE OF CONES AS STABILIZING AND CONTROL SURFACES AT HYPERSONIC SPEEDS

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SUMMARY

A brief study has been made of the use of cones as stabilizing and control surfaces at hypersonic speeds. The results indicate that in this application cones may offer several advantages over more conventional surfaces.

INTRODUCTION

At hypersonic speeds adequate aerodynamic stability and control are difficult to obtain by conventional aerodynamic surfaces such as used at subsonic and low supersonic speeds. Because of loss in effectiveness with increasing Mach number, planar surfaces are often not suitable at hypersonic speeds; even as canards they suffer from the inherent shortcomings of low lift-curve slopes. This deficiency in lift-curve slope and the resulting adverse effects upon the stability and control of hypersonic airplanes and missiles have led to the proposal of methods for alleviating this difficulty. One such proposal, given in reference 1, is the use of simple two-dimensional wedges for the stabilizing surfaces; thereby, advantage can be taken of the large increase in lift-curve slope that wedges exhibit at hypersonic speeds. A cone also has considerably higher lift-curve slopes than the flat plate at hypersonic speeds and, as shown in reference 2, is relatively efficient for developing lift. (As constrasted with the two-dimensional wedge, the conical surface may be thought of as wedging out the flow three dimensionally and, thereby, gains a lift advantage over the flat plate in the same manner as for the two-dimensional wedge, but of different magnitude.) In particular, a conical surface (not necessarily circular in section) has attractive features as a stabilizing and control surface for hypersonic flight that are not common to two-dimensional wedges or planar surfaces. The purpose of this paper is to describe these features and to present the results of a brief study of this application of conical surfaces.

SYMBOLS

$C_{D,b}$	base drag coefficient
$C_{D,f}$	skin-friction drag coefficient
$C_{D,p}$	forebody-pressure drag coefficient
$C_{D,t}$	total drag coefficient, $C_{D,p} + C_{D,f} + C_{D,b}$
C_f	average skin-friction coefficient
C_{l_β}	effective-dihedral derivative
C_{l_δ}	roll-control parameter for total roll-control deflection
C_{N_α}	rate of change of normal-force coefficient with angle of attack
C_{n_β}	directional-stability derivative
C_p	pressure coefficient
M_∞	free-stream Mach number
T_W	absolute temperature at wall
T_δ	absolute temperature at outer edge of boundary layer
α	angle of attack
θ	semiapex angle of cone or wedge
μ_∞	Mach angle, $\sin^{-1}\frac{1}{M_\infty}$
γ	ratio of specific heats, 1.40

Subscripts:

b	base
c	circular cone

pc pyramidal cone

w wedge

DISCUSSION

Preliminary Considerations

The cone of circular cross section has the obvious but unique quality of having the same lift-curve slope regardless of the meridian plane in which it is yawed with respect to the relative wind. This quality in itself makes the circular cone an attractive stabilizing surface since, in contrast with the planar or two-dimensional wedge surface, the circular cone, if properly located, would have essentially the same effectiveness regardless of the meridian plane in which the airplane is upset, that is, in pitch, yaw, or combined pitch and yaw. When the cone is given the ability to deflect in both pitch and yaw simultaneously, it becomes an effective control surface as well. For example, two cones capable of pitch, yaw, and differential pitch are sufficient to obtain longitudinal and directional stability and control as well as roll control. A midwing hypersonic airplane that might employ cones in this manner at the tip of the wings is illustrated in figure 1. These cones could be either pyramidal or circular as shown. If the cones are placed in a lateral plane passing close to or through the center of gravity of the airplane and in positions that are exposed to minor or essentially identical interference fields, the effective-dihedral derivative C_{l_β} will be near zero[1]; this would appear to be a desirable feature in view of stability troubles that have been exposed in studies of proposed hypersonic airplanes for which C_{l_β} is not near zero.

Conical tip controls, such as those illustrated for the configuration in figure 1, should provide ample static directional stability (at $M_\infty = 12$ and moderate angles of attack, values of C_{n_β} of 0.001 appear reasonable), and their effectiveness should not change much with angle of attack of the airplane, as is the case with directional control and stabilizing surfaces placed in the vertical plane of the center of gravity. In addition, these controls would not operate in the ineffective flow field or "hypersonic shadow" of the wing or fuselage and would, therefore, not experience the loss in effectiveness associated with

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[1]Slight changes in wing dihedral of a configuration having a low wing or high wing afford an easy means of placing the cones in a lateral plane so that C_{l_β} is near zero at angles of attack in the vicinity of that chosen for $C_{l_\beta} = 0$.

operating in the shadow. Conical tip controls should also provide adequate roll control (at $M_\infty = 12$ values of C_{l_δ} of 0.0005 appear reasonable). An attractive but perhaps less important feature is that the shape and the location of the center of pressure of a cone at its center of area afford an easy means of obtaining essentially zero hinge moment in both pitch and yaw, if desired.

The following two sections of the report deal with the circular cone and consider the cone angles of probable interest and the lift advantage of the cone over the flat plate. Subsequently, comparisons are made of the circular cone, the pyramidal cone, and the two-dimensional wedge. These latter comparisons might be termed isolated comparisons, since they compare single units (such as a single wedge with a single cone) on the basis of same plan-form area, length, and semiapex angle. These comparisons should, therefore, not be regarded as the final objective from a stability viewpoint but as a means for enabling one to examine the penalties and advantages that would accrue to a given configuration when the configuration is equipped with the necessary number and size of units to produce a given restoring force. For example, a given configuration may require more wedges than cones to achieve the same stability, but the individual wedges might be smaller than the individual cones; it is this situation that one wishes to examine ultimately.

Range of Cone Angles of Probable Interest

Figure 2 presents the slope of the normal-force-coefficient curve C_{N_α} for circular cones (referred to base area) as a function of cone semiapex angle θ_c for several Mach numbers. These values are taken from reference 3. For values of θ_c less than about 12° to 15°, C_{N_α} does not vary much with either Mach number or cone angle, as was observed in the slender-cone hypersonic analysis of reference 2. For $M_\infty \gtrsim 4$, C_{N_α} begins to decrease noticeably as θ_c is increased beyond the order of 15°. Thus, for a circular cone to be used as a control and stabilizing surface, values of θ_c less than about 15° appear to be preferable if high lift effectiveness is to be maintained.

The use of very small cone angles would be undesirable for several reasons. For a given base area of the cone, the weight of the cone may be assumed to increase, at least to first order, in proportion to its surface area or as $\frac{1}{\sin \theta_c}$. Thus, from a weight standpoint very small cone angles are unattractive and from a structural standpoint would lead to large and unwieldy surfaces.

Perhaps the most important reason for avoiding small cone angles is illustrated in figure 3 where the manner in which the lift advantage shifts from the flat plate to the cone is shown for Mach numbers of 2 and 10. The flat plate is assumed to be two dimensional, that is, no tip losses (tip losses at high M_∞ become negligible), and the calculations are for small angles of attack or, rigorously, are based on the slopes at zero angle of attack[2]. The comparison is based on the requirement that the cone and flat plate are to have the same projected plan-form area. The disadvantage of very small cone angles is clearly shown in that, at $M_\infty = 10$, θ_c must be greater than about 4° for the lift advantage to shift to the cone. For lower Mach numbers larger values of θ_c are required to bring about the shift in lift advantage, the converse being true for higher Mach numbers. A rough and very conservative estimate of the value of θ_c for which the lift advantage shifts to the cone at any Mach number is given simply by the Mach angle, that is, $\theta_c = \mu_\infty$. This Mach angle estimate gives $\theta_c = 30^\circ$ for $M_\infty = 2$ and $\theta_c = 5.74^\circ$ for $M_\infty = 10$, both of which are a degree or two higher than the values indicated in figure 3 for the shift in lift advantage.

It is somewhat difficult to define closely a practical lower limit for θ_c but, in view of the above indications and of the desirability of having the cone normally operate in a range of pitch and yaw angles not much greater than θ_c in order to be most effective, values of θ_c in the neighborhood of 7° to 15° appear to cover the range of practical interest. The probability that values of θ_c much lower than 7° will not be desirable infers that the value of θ_c will quite likely be larger than the optimum value of θ_c $\left(\text{value for largest } \left(\frac{L}{D}\right)_{max}\right)$ since the optimum value is usually less than 7°. An example of this is given in figure 4 where $\left(\frac{L}{D}\right)_{max}$ as a function of θ_c has been estimated for the arbitrarily selected conditions shown in the figure. The present estimate utilizes the lift-curve slopes of reference 3, assumes a vacuum to exist on the base of the cone, and accounts for the change in skin-friction drag associated with the change in Reynolds number with cone length. For this example the optimum value of θ_c is observed to be about 3.5°. The slender-cone analysis of reference 2 gives somewhat higher values of $\left(\frac{L}{D}\right)_{max}$ than the present estimate but gives excellent agreement with the optimum value of θ_c. From the standpoint of aerodynamic efficiency of the cone only, and within the probable range of practical interest (about 7° to 15°), the lower cone angles are to be preferred.

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[2]Although all the numerical results are rightfully restricted to small angles of pitch and yaw, the general indications hold for larger angles.

Effects of Mach Number Upon Shift in Lift

Advantage From Flat Plate to Cone

The curves in figure 3, by comparison at a given value of θ_c, have already indicated the shift in lift advantage from the flat plate to the circular cone that occurs as Mach number is increased. However, it is of interest to examine explicitly the probable Mach number range in which the shift in lift advantage will occur. This range is indicated in figure 5 for three cone angles. If the planar surface is considered to be a flat plate with no tip losses (two dimensional), the lift advantage shifts to the cone near $M_\infty = 8$ for $\theta_c = 5^\circ$, near $M_\infty = 4$ for $\theta_c = 10^\circ$, and near $M_\infty = 3$ for $\theta_c = 15^\circ$. This comparison, while encouraging the use of cones at hypersonic speeds, might be interpreted, however, as not doing the cone full justice. A comparison (which while realistic may, from a practical view, be slightly optimistic with respect to the cone) with a flat-plate delta wing, apex forward and having the same semiapex angle as the cone, shows the advantage to shift to the cone near $M_\infty = 2$ for the values of θ_c of probable interest (about 7° to 15°). The ordinate of figure 5 may also be regarded as the ratio of the area of the flat plate to the plan-form area of the cone that is required to produce the same lift at the same angle of attack, or as the ratio of α of the flat plate to α of the cone required to produce the same lift for the same plan-form area.

Comparison of Cone With More Competitive Lifting Surfaces

Preliminary remarks.- The comparisons that follow are for single units (for example, a single wedge compared with a single cone). As stated previously, these comparisons are regarded as furnishing a means whereby one may weigh the merits of one type of stabilizing surface against another when the number and size of surfaces are established on the basis of providing the same restoring force.

Lift comparisons.- Thus far, the circular cone has been shown to be a considerably better lifting surface at hypersonic speeds than the flat plate. Figure 6 shows the lift advantage that a two-dimensional wedge has over a circular cone. The values of C_{N_α} for the wedge were obtained from reference 1. The C_{N_α} ratios shown in figure 6 lose some of their practical significance at the lower Mach numbers since, for most applications, the regions in which the flow over a wedge surface of finite span is not two dimensional become sufficiently large, as the Mach number is decreased below the order of 4, to bring about a significant reduction in lift below the two-dimensional lift. At high Mach numbers, and for the range of cone angles indicated previously to be attractive (order of 7° to 15°), the two-dimensional wedge is indicated to have about one and one-half times the lift of the circular cone.

If the cone were pyramidal, the lift advantage of the two-dimensional wedge would be reduced. No attempt has been made to estimate this reduction, but it is clear that the lifting pressures on the pyramidal cone would be greater than those for the circular cone and less than those for the two-dimensional wedge. The pyramidal cone could, of course, be used in the same manner as the circular cone, as shown in figure 1. The pyramidal cone would not have the quality of the circular cone in producing the same restoring force regardless of the meridian plane in which the cone is yawed, but its disadvantage in this respect is, of course, nowhere near that of the two-dimensional wedge and may not be objectionable in some installations.

Drag comparisons.- The drag comparisons of the circular cone, pyramidal cone, and two-dimensional wedge may be made in a number of ways. The comparisons presented herein are made at zero lift on the basis of the same plan-form area, semiapex angle θ, and length. (The length is always taken in the streamwise direction, and the plan-form area of the wedge is always taken as that parallel to the plane of symmetry that contains the leading edge of the wedge.) The use of the same plan-form area and θ is compatible with the lift comparisons and thereby affords direct comparisons of the lift and drag advantages and disadvantages. The use of the same length was chosen so that it may be assumed that for the same flight conditions the average skin-friction coefficient C_f is the same. (Rigorously, there would be small differences in C_f associated with shape. See summary of conversion of skin-friction coefficients given in ref. 4.)

As an estimate of base drag it is assumed that the base pressure coefficient is equal to $-\frac{1}{M^2}$. Examination of the results of reference 5 for turbulent boundary layers shows that this approximation satisfactorily predicts the base pressure coefficient for a two-dimensional base and for a cone with $\theta_c = 15^\circ$ provided M_∞ is greater than about 2. For laminar boundary layers the base pressure would be expected to increase, and at hypersonic speeds the effects of vorticity may cause a further increase; however, at hypersonic speeds the exact value of the base pressure coefficient is relatively unimportant since at worst it can be no less than $-\frac{2}{\gamma M_\infty^2}$. With the above conditions imposed the following expressions are obtained for the total drag coefficients. For the two-dimensional wedge,

$$C_{D,t,w} = 2C_{p,w} \tan \theta_w + 4C_f + \frac{2}{M_\infty^2} \tan \theta_w \qquad (1)$$

For the circular cone,

$$C_{D,t,c} = \pi C_{p,c} \tan \theta_c + \pi C_f + \frac{\pi}{M_\infty^2} \tan \theta_c \tag{2}$$

For the pyramidal cone,

$$C_{D,t,pc} = 4C_{p,pc} \tan \theta_{pc} + 4C_f + \frac{4}{M_\infty^2} \tan \theta_{pc} \tag{3}$$

The first right-hand term in each of the above equations is the forebody pressure drag coefficient $C_{D,p}$, the second is the skin-friction drag coefficient $C_{D,f}$, and the third is the base drag coefficient $C_{D,b}$. For the two-dimensional wedge there may be some applications in which it would not be reasonable to charge the flat sides of the wedge (those sides alined with the stream) with skin-friction drag, such as the variable wedge with open sides. In such applications the second term of equation (1) would be $2C_f$. For evaluating these equations, values of $C_{p,c}$ and $C_{p,w}$ may be obtained from reference 3.

The ratios of the component drags (forebody pressure, skin friction, and base) of the two-dimensional wedge and of the pyramidal cone to the corresponding component drag of the circular cone having the same θ may be readily obtained from the preceding equations, if desired.

It is physically obvious that the forebody-pressure drag for the pyramidal cone is always greater than that for the circular cone, since $C_{p,pc}$ can be no less than $C_{p,c}$ and in fact may be nearer $C_{p,w}$. In the case of the two-dimensional wedge, it is well known that at supersonic speeds the wedge has a forebody pressure drag greater than that for the circular cone of equal plan-form area. It is perhaps not so fully appreciated that the reverse is true at hypersonic speeds; the reversal occurs because $C_{p,w}$ tends toward $C_{p,c}$ as M_∞ increases. The dashed curves of figure 7 show that the value of M_∞ for which this reversal occurs ranges from near 9 for $\theta = 5^\circ$ to about 3.5 for $\theta = 15^\circ$. Also shown in figure 7 are the curves for the pyramidal cone with $C_{p,pc} = C_{p,w}$ and with $C_{p,pc} = C_{p,c}$. The actual forebody-pressure-drag ratios for the pyramidal cone would lie somewhere between the solid curves and the value $\frac{4}{\pi}$, as indicated by the dash-dot curve.

The skin-friction drag for the two-dimensional wedge and that for the pyramidal cone are equal but are greater than that for the circular cone by the factor $\frac{4}{\pi}$ (excluding the special case of the wedge with no sides). A clearer picture of the relation of the wedge to the circular cone may be had by recognizing that the wedge having the same length and plan-form area as the cone has a width equal to the base radius of the cone.

The base drag for the wedge is less than that for the circular cone, the converse being true for the pyramidal cone.

The ratios at zero lift of the total drag of the wedge and of the pyramidal cone are of particular interest. These ratios have been computed for values of C_f of 10^{-2}, 10^{-3}, and 10^{-4} from equations (1) to (3). The results for the wedge are shown in figure 8 and those for the pyramidal cone in figure 9.

The curves of figure 8 show that increasing θ from 5° to 15° has the effect at hypersonic speeds of placing the wedge in a more favorable light; however, the importance of this effect of increasing θ becomes trivial with decreasing C_f. In general, the wedge is indicated to have from about the same drag to about 25 percent less drag than the circular cone for the values of θ of probable interest (about 7° to 15°).

The curves of figure 9 show that the drag of the pyramidal cone is, as is to be expected, always greater than that for the circular cone; at hypersonic speeds the drag of the pyramidal cone is of the order of 30 to 50 percent greater than that for the circular cone. (The drag ratio lies somewhere between the dashed curve and the solid curves in fig. 9.) At $C_f = 10^{-2}$ the effect of increasing θ is opposite to that for the wedge. At lower C_f the effect of θ is unimportant at hypersonic speeds in the range of θ of probable interest.

Interpretation of Unit Comparisons in Terms of Producing Same Restoring Force for Complete Configuration

The comparisons of single units at hypersonic speeds have indicated that the two-dimensional wedge has a lift advantage over the circular cone of the order of 50 percent and a drag ranging from about the same to about 25 percent less than the circular cone (for cone angles from about 7° to 15°). It remains, however, to interpret these results in terms of providing equal restoring force, maintaining effectiveness, and supplying roll, pitch, and yaw control. Obviously, one can conceive of several arrangements of stabilizing and control surfaces in which the number of units involved is different. For example, four wedges might be employed (one at each wing tip, and above and below the fuselage), three wedges might be employed (one beneath fuselage and one at each wing tip), or two wedges might be used in a drooped wing-tip arrangement.

However, whether these arrangements or others are employed, a cursory examination indicates that the general conclusions drawn from the following example based on the use of four wedges would apparently hold good in view of the change in the size of the wedges with arrangement and the stability problems that are associated with different arrangements.

Whereas roll, pitch, and yaw control, longitudinal stability, and directional stability can be provided by two circular or pyramidal cones on a configuration of the type shown in figure 1, the same configuration would probably require four wedges as described above to achieve the same degree of stabilization and control while maintaining C_{l_β} near zero. (When interference effects are considered, it is very doubtful that the wedge-equipped configuration can maintain C_{l_β} near zero at other than small pitch or yaw.) On the basis of the same plan-form areas this would mean that the total drag ratios of figure 8 would be increased by a factor of 2 and, therefore, that the total drag of the stabilization and control surfaces of the wedge-equipped hypersonic configuration would be of the order of 1.5 times that of the configuration equipped with circular cones. However, this view must be tempered by the fact that the wedges under consideration have approximately 50 percent greater lift than the circular cone at hypersonic speeds, as indicated in figure 6. Alternatively expressed, the wedge needs only about 65 percent of the plan-form area of the circular cone having the same θ in order to produce the same lift. When this need for lesser area is taken into account, the drag disadvantage of the wedge is reduced. For example, with $M_\infty = 10$, $\theta = 10^\circ$, and $C_f = 10^{-3}$, the drag of the four wedges would be about 9 percent greater than that of two circular cones. Thus, in consideration of only the total drag of the complete configuration, the drag differences between the wedges and the cones required to produce the same degree of stabilization and control would not appear to weigh heavily in the choice between cones and wedges. Drag estimates at $M_\infty = 12$ for configurations of the type shown in figure 1 indicate that two cones capable of supplying ample roll, pitch, and yaw control would contribute in the neighborhood of 6 to 16 percent of the total drag of the configuration. Consequently, in this example the total drag of the wedge-equipped configuration would be only about 1 percent greater than that of the cone-equipped configuration.

The pyramidal cone also produces greater lift than the circular cone of the same plan-form area, but it also has greater drag. Inasmuch as this lift advantage of the pyramidal cone is directly associated with most of its drag disadvantage, one may reasonably conclude that the pyramidal cone (of reduced plan-form area) producing the same lift as the circular cone having the same θ would have, to a first approximation at least, a drag comparable to that of the circular cone.

Thus, the choice between wedges and cones for use as stabilizing and control surfaces at hypersonic speeds would appear to hinge upon such features as maintaining effectiveness with change in attitude as well as small C_{l_β}. For reasons that have already been given earlier in this paper in the section entitled "Preliminary Considerations," the use of cones as proposed herein is believed to offer the better opportunity for realizing these features. In line with all of the preceding discussion there is a general fundamental justification for the use of cones at hypersonic speeds. For configurations of the type shown in figure 1 the directional stability characteristics of the basic airplane without stabilizing surfaces are determined primarily by the lift that bodies of revolution, or segments thereof, can develop and how this lift varies with Mach number. Consequently, if the stabilizing surfaces had the lift behavior of a body and similar small changes in lift-curve slope with Mach number, the configuration should tend to take care of itself, so to speak, with increasing Mach number. Thus, a logical choice of a stabilizing surface to offset body or fuselage instability would appear to be another body; in this study a cone has been chosen. Since the lift-curve slopes of bodies do not change much with Mach number, the cone size chosen to give stability at Mach numbers bordering on hypersonic speeds should be, to first order at least, satisfactory at higher Mach numbers.

CONCLUDING REMARKS

In this paper it has been shown that cones suitable for use as control and stabilizing surfaces at hypersonic speeds have lift-curve slopes that are much larger than those of the flat plate and of the same order as those of two-dimensional wedges. For a hypersonic-airplane configuration of the type illustrated in figure 1, the drag contributed by circular-cone-type stabilizing and control surfaces has been indicated to be negligibly different from that of wedge-type surfaces, when one type of surface is required to produce the same restoring force as the other type in both pitch and yaw (interference effects neglected). Thus, at hypersonic speeds the choice between wedges and cones will not be influenced by drag considerations; rather the choice resolves itself to one based primarily upon achieving the highly desirable features of maintaining the necessary degree of stabilization and control as nearly invariant with attitude of the airplane as possible while maintaining the effective dihedral derivative C_{l_β} near zero. Circular cones are believed to offer a better opportunity for realizing these features for several reasons. To begin with, instability at hypersonic speeds is usually associated with body forces. It seems logical, therefore, to use another body as a stabilizing surface to offset this instability; in this study a cone has been chosen. The circular cone is unique, in the absence of interference forces, in exhibiting the same restoring force in all meridians of yaw. For a highly swept delta-wing configuration with the cones at the wing tips, the cones should experience little change in pitch or yaw effectiveness with attitude of the airplane, and there is good reason to feel that values of C_{l_β} near zero can be achieved and maintained. By contrast, wedges employed as vertical-tail surfaces above and below the fuselage (or above and below the wing) would experience marked changes in effectiveness since the upper and lower tails would operate in widely different flow fields at angles of attack much removed from zero. It follows that C_{l_β} for these wedge-equipped configurations would probably undergo significant variation and, consequently, that there is little hope of maintaining C_{l_β} near zero for wedge-equipped configurations.

The pyramidal cone also shows promise and may prove to be satisfactory in achieving the desired features mentioned above.

Because of the limited scope of this study, no attempt has been made to estimate how problems of aerodynamic heating might enter into the choice of stabilization and control surfaces. Undoubtedly, any effective stabilization and control surface will encounter some heating problems at hypersonic speeds.

The possibility of varying the wedge angle in flight is an attractive feature of the wedge for use at Mach numbers below the design value, as pointed out in NACA RM L54F21. This feature could also be incorporated in a pyramidal cone. Other devices, such as a telescoping skirt, offer similar advantages to a circular cone.

In summary, the use of cones as stabilizing and control surfaces at hypersonic speeds appears feasible and attractive.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 29, 1957.

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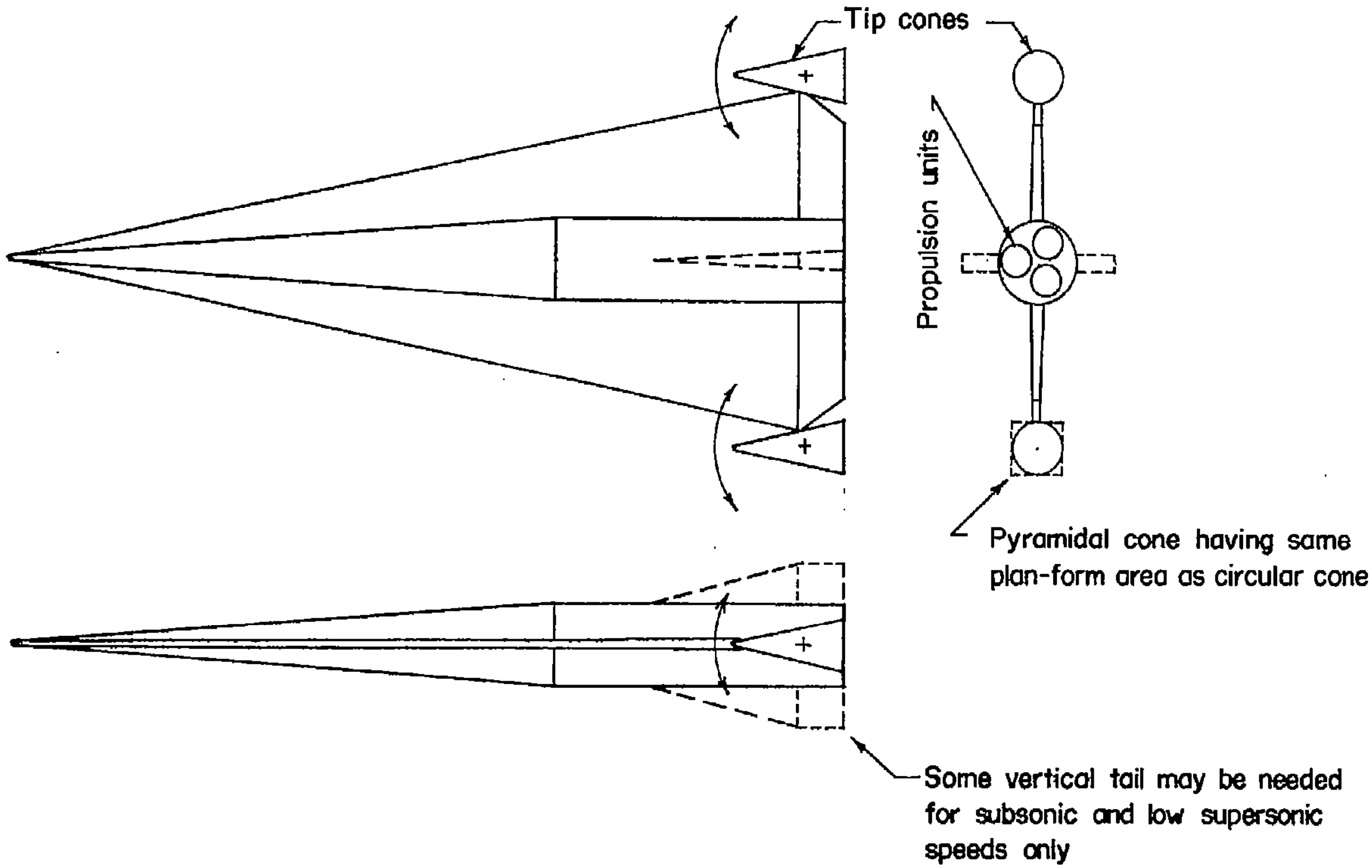

Figure 1.- Sketch of hypersonic-airplane configurations employing cones for stabilization and control.

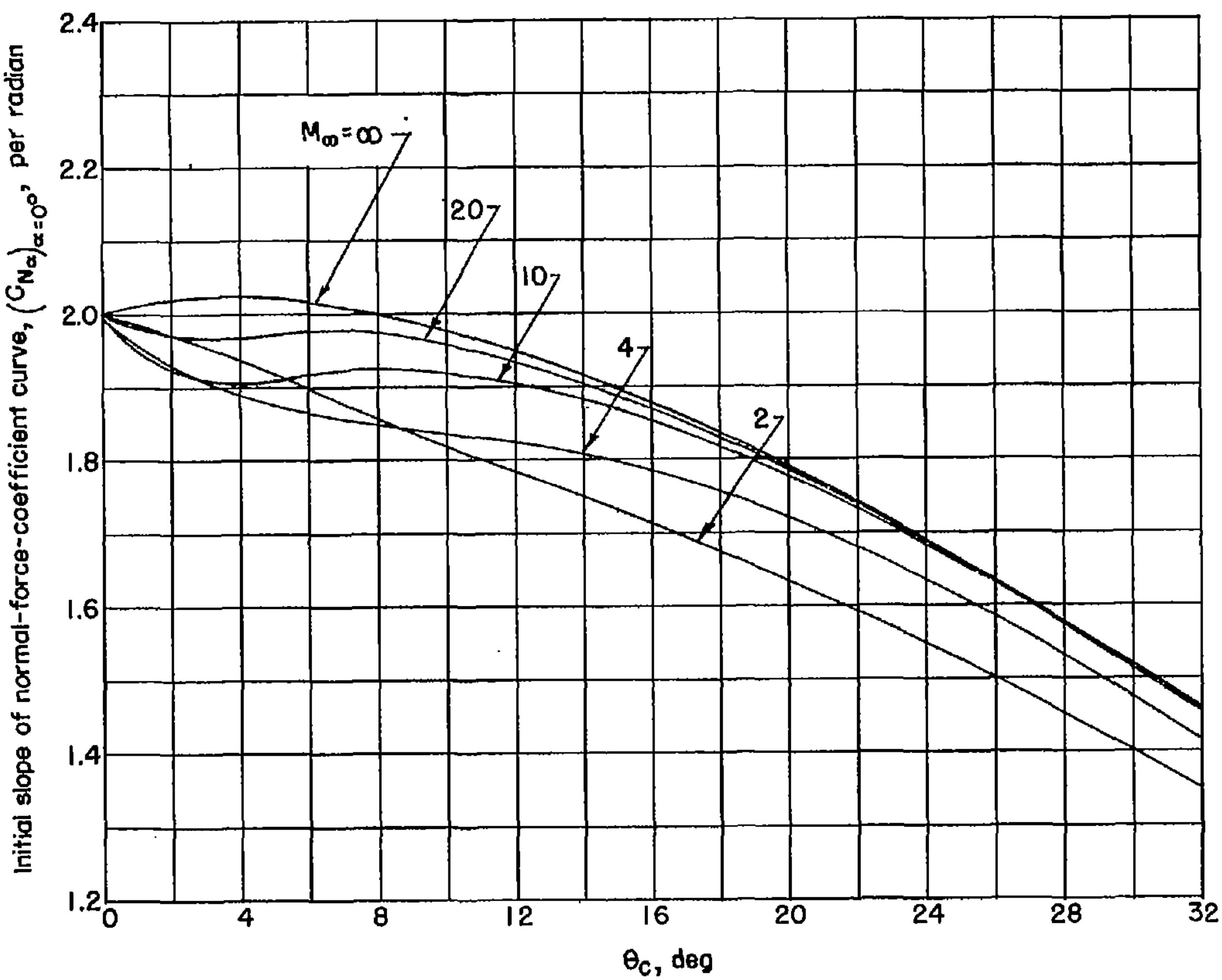

Figure 2.- Variation of the initial slope of the normal-force-coefficient curve with cone semi-apex angle for circular cones at several Mach numbers (from ref. 3).

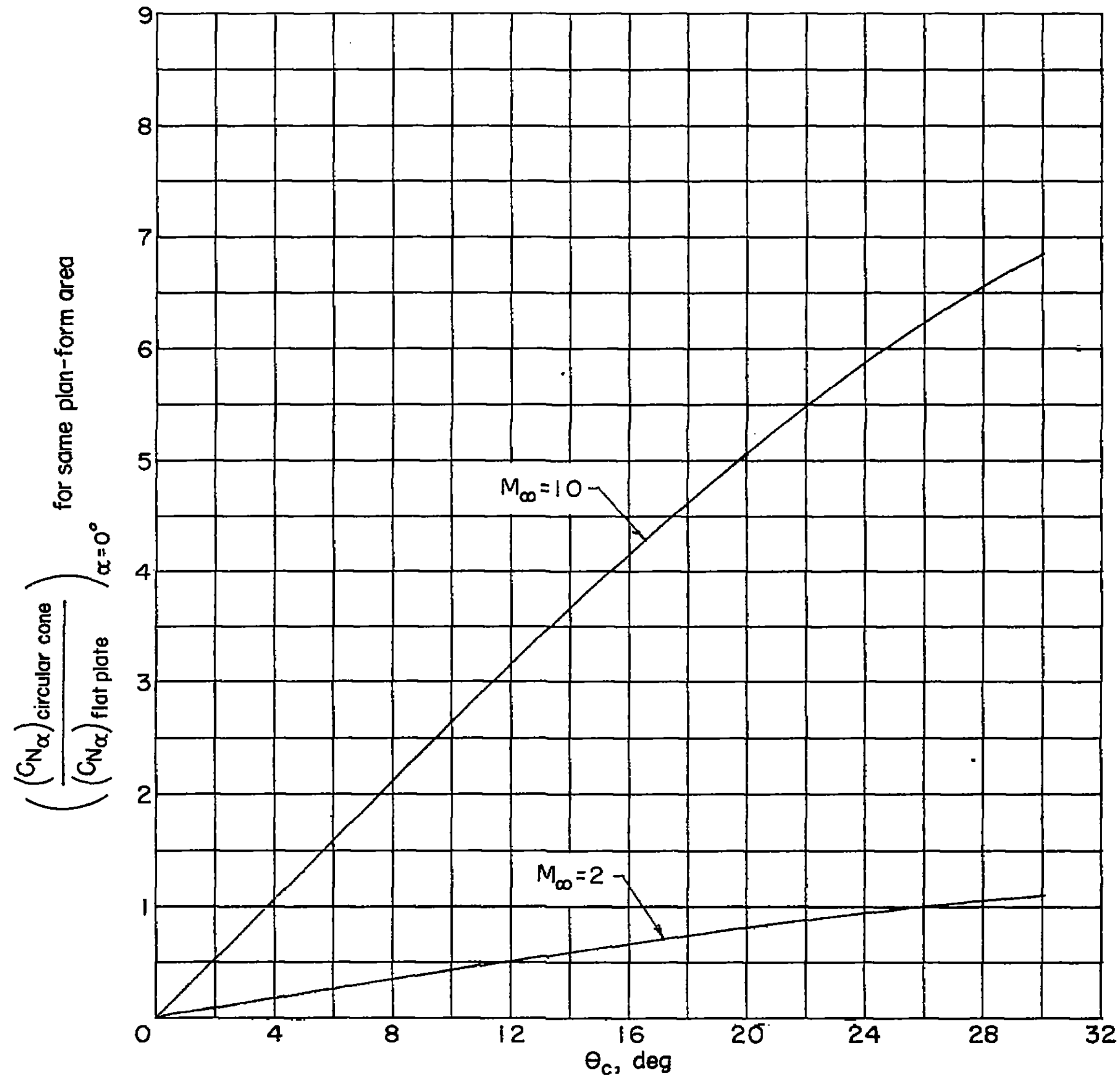

Figure 3.- Example of shift in lift advantage from flat plate to circular cone of same plan-form area with varying semiapex angle of the cone.

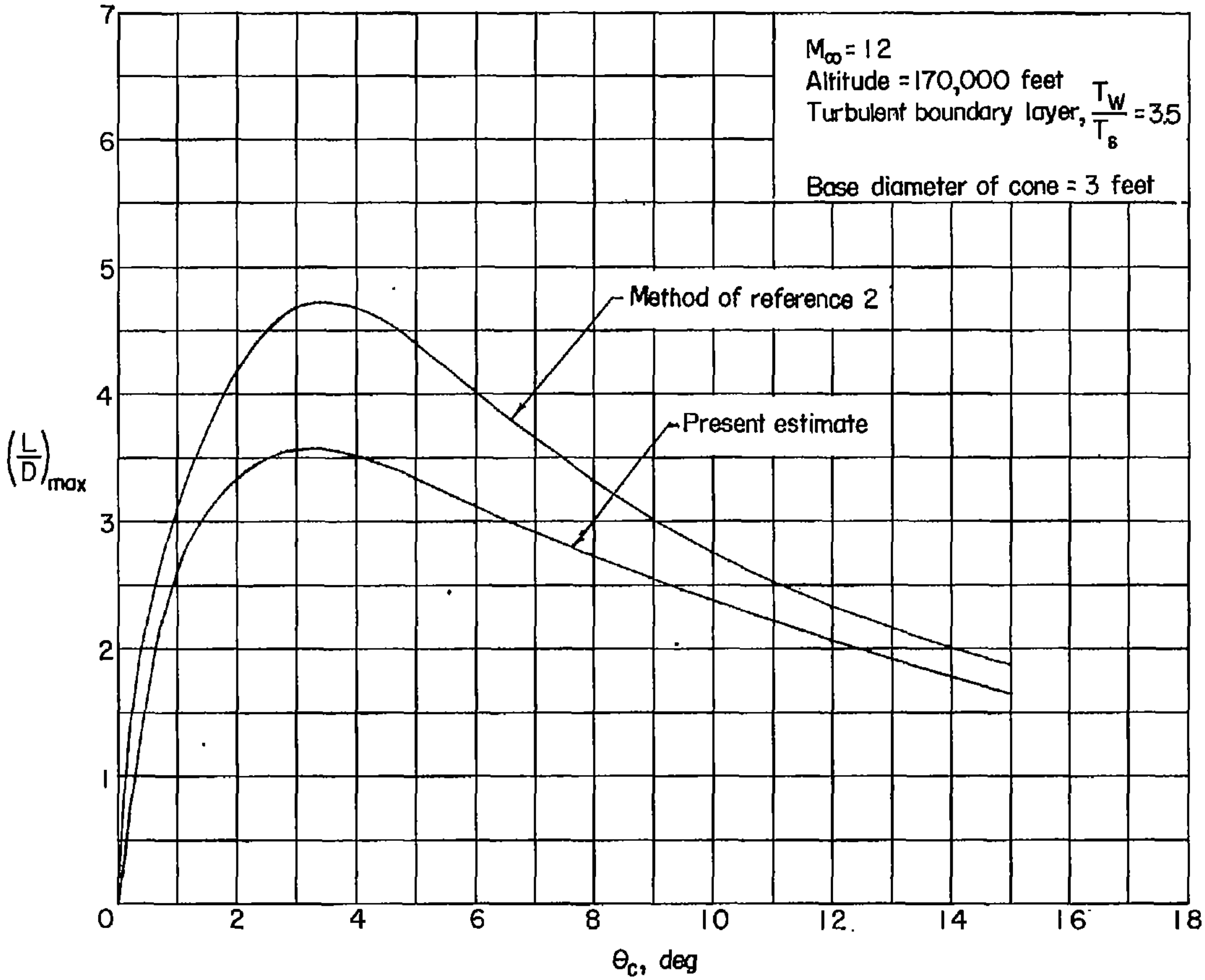

Figure 4.- Example of variation of maximum lift-drag ratio with semiapex angle of circular cone.

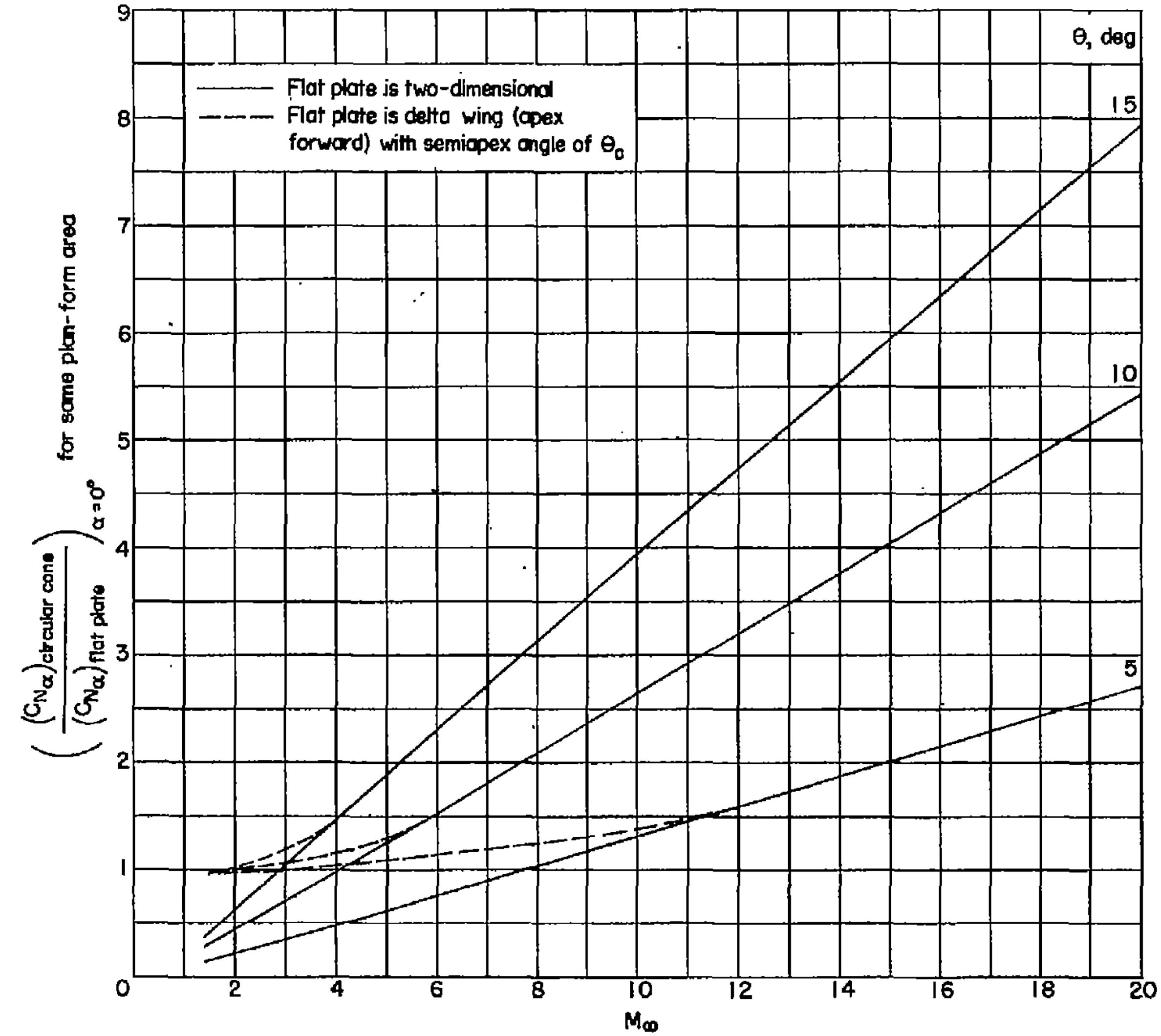

Figure 5.- Variation with Mach number of the ratio of initial slope of normal-force-coefficient curve of circular cone to that of flat plate for same plan-form area.

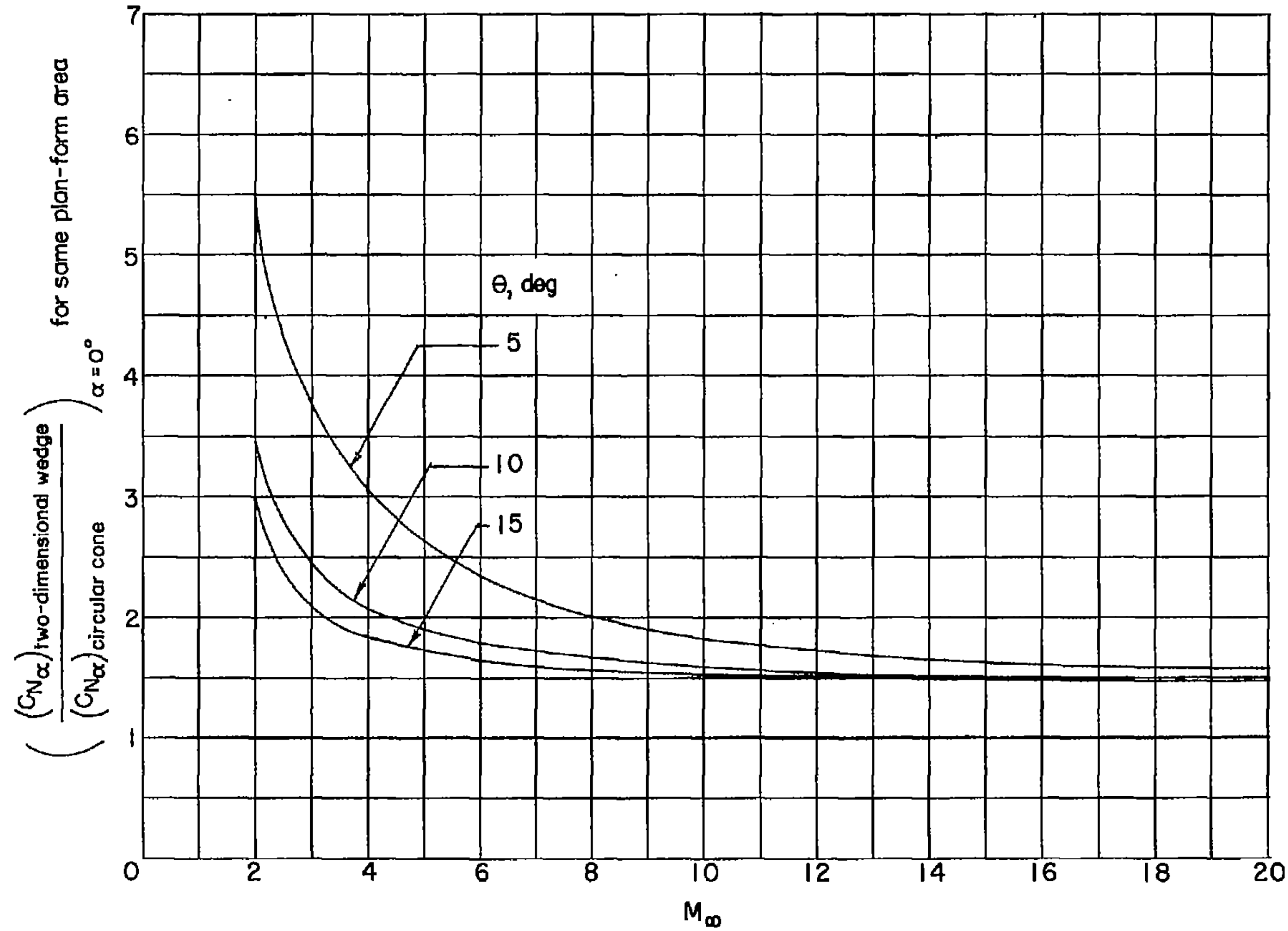

Figure 6.- Variation with Mach number of the lift advantage of a two-dimensional wedge over a circular cone.

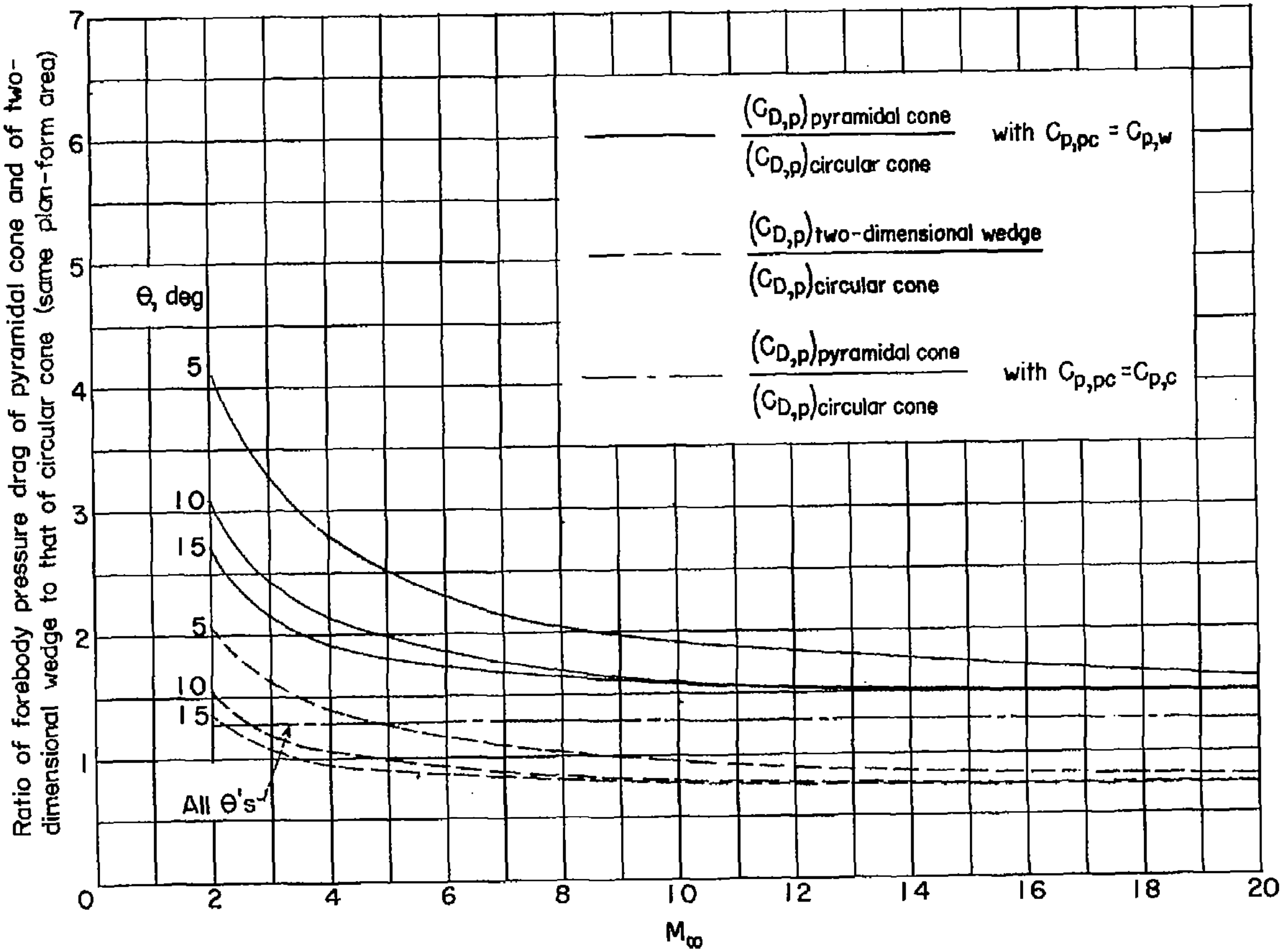

Figure 7.- Variation with Mach number of the ratio of forebody pressure drag of pyramidal cone and of two-dimensional wedge to that of circular cone.

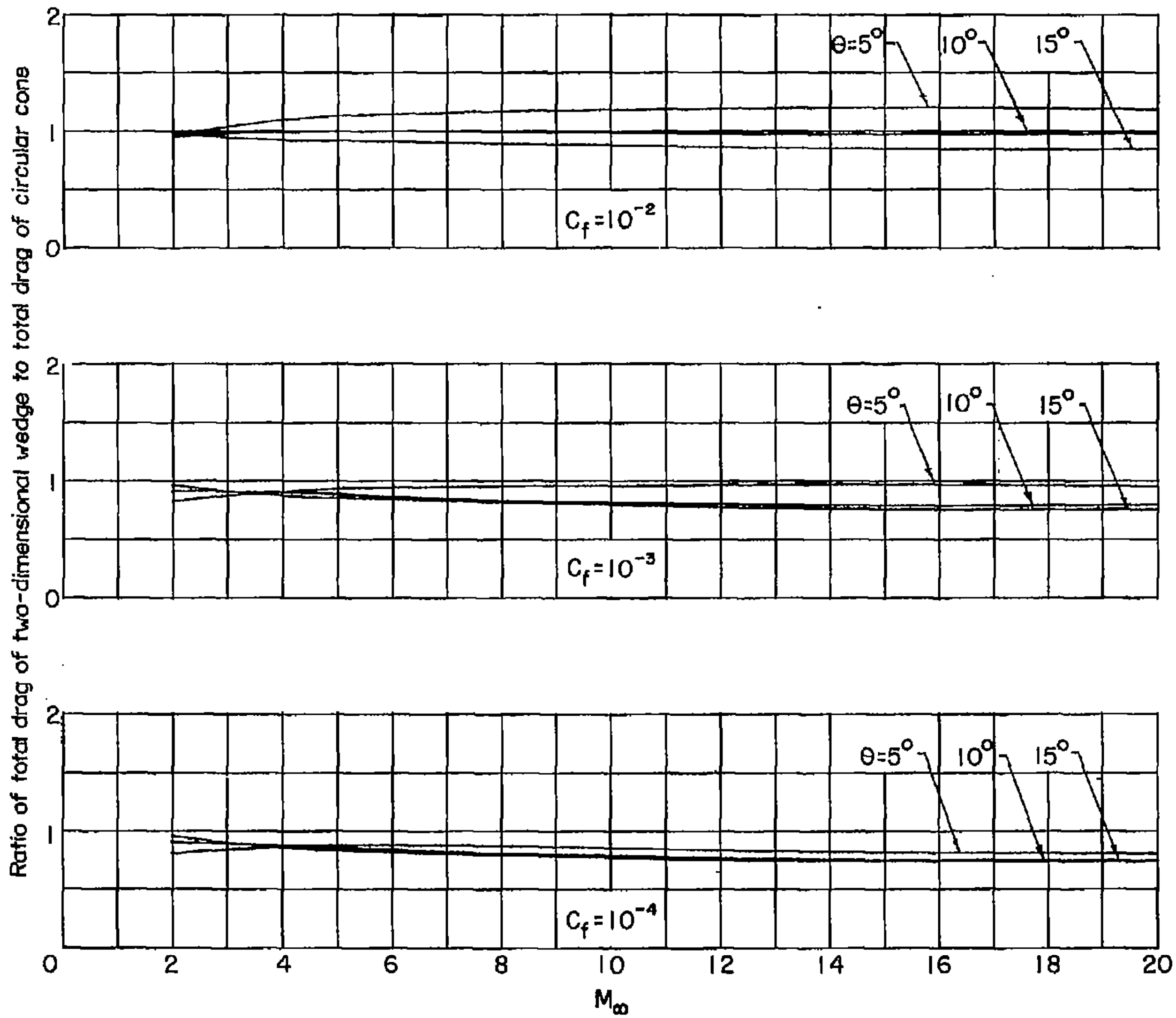

Figure 8.- Variation with Mach number of the ratio of the total drag of a two-dimensional wedge to that of a circular cone having same length, plan-form area, and θ.

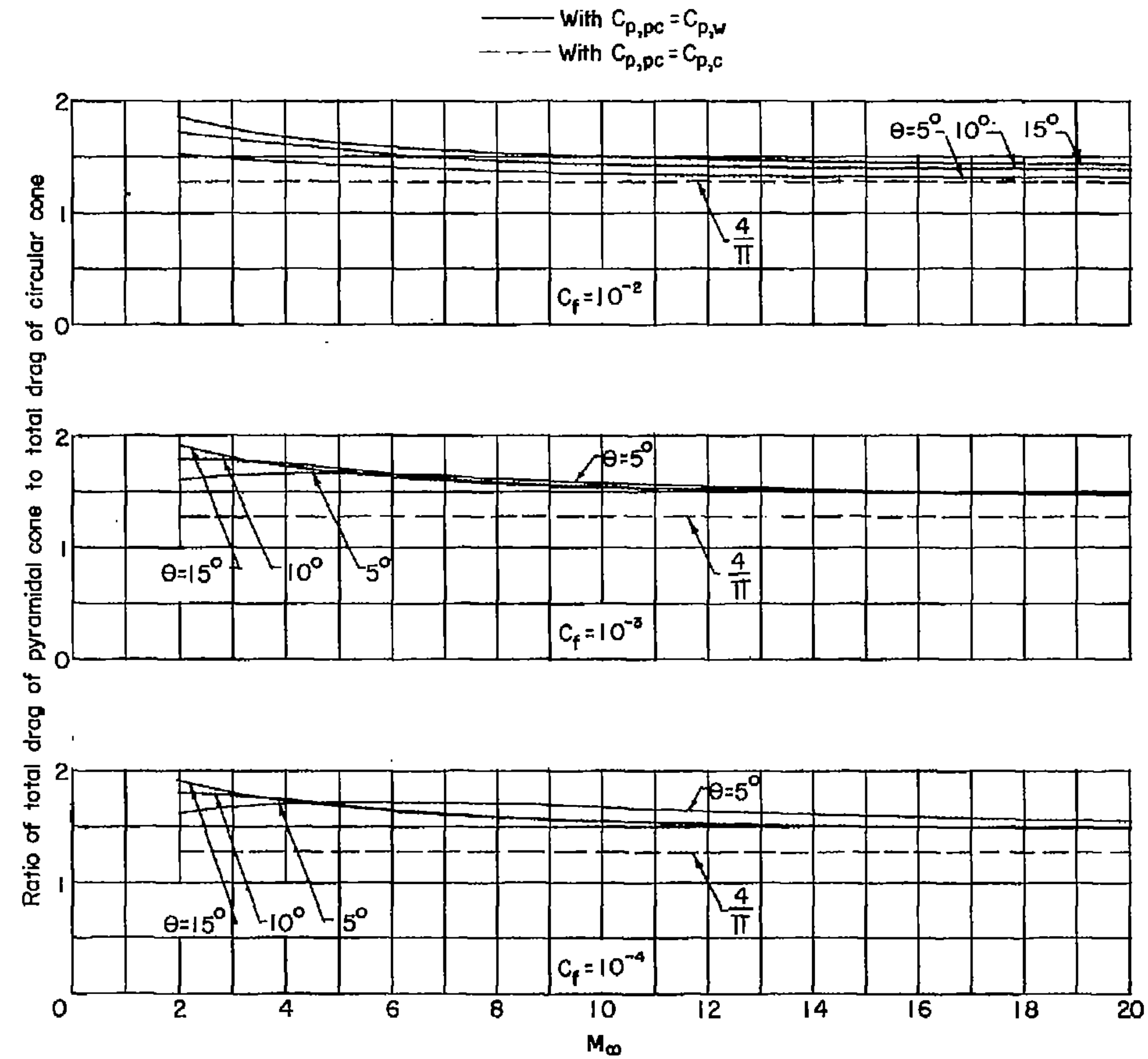

Figure 9.- Variation with Mach number of the ratio of the total drag of a pyramidal cone to that of a circular cone having same length, plan-form area, and θ.